

Transport model analysis of particle correlations in relativistic heavy ion collisions at femtometer scales

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Abstract

The pion source as seen through HBT correlations at RHIC energies is investigated within the UrQMD approach. We find that the calculated transverse momentum, centrality, and system size dependence of the Pratt-HBT radii R_L and R_S are reasonably well in line with experimental data. The predicted R_O values in central heavy ion collisions are larger as compared to experimental data. The corresponding quantity $\sqrt{R_O^2 - R_S^2}$ of the pion emission source is somewhat larger than experimental estimates.

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In the quest to discover the high temperature phase of Quantum Chromodynamics (QCD), the Quark Gluon Plasma (QGP), the beam energies of accelerators have been boosted upwards from SIS, AGS, SPS, to RHIC. However, it is well known that the phase transition from hadrons to quarks might only occur in a small volume part of the system and within a rather short timespan in heavy ion collisions (HICs). This implies that the QGP drops formed at RHIC might be represented only by a few, locally thermally equilibrated drops of matter, in which quarks and gluons are de-confined. Thus, it is essential to probe the space-time structure of the (equilibrated?) source – the "region of homogeneity". Unfortunately, the small size and transient nature of the reactions preclude direct measurement of the time and/or position. Instead, correlations of two final-state particles at small relative momenta provide the most direct link to the size and lifetime of subatomic reactions. A well-established technique, the so-called "femtoscopy" or "HBT" in the heavy-ion community (in reference to Hanbury-Brown and Twiss's original work with photons) has been extensively used for HICs with energies from SIS, AGS, SPS, to RHIC [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31].

Numerous HBT-measurements with various two-particle species have been pursued (see e.g. [1, 16] and references therein). Identically charged pion interferometry has been most extensively investigated. Basic, but important systematics of femtoscopic measurements from the AGS, SPS, and RHIC have been discovered [1, 7, 14, 16], such as the dependence of the HBT radii on system size, collision centrality, rapidity, transverse momentum, and particle mass. However, the existence of the so-called HBT-puzzle (i.e., the fact that model calculations that incorporate a phase transition to a new state of matter with many degrees of freedom significantly over-predict the observed source sizes) [1, 4, 19, 20, 21, 27, 28, 32, 33] drives us to a deeper and more systematical theoretical exploration. The Ultra-relativistic Quantum Molecular Dynamics (UrQMD, v2.2) transport model (employing hadronic and string degrees of freedom) (for details, the reader is referred to Refs.[34, 35, 36, 37]) and the analyzing program CRAB (v3.0 β) [38, 39, 40] are employed here as tools to analyze the two-particle interferometry. It is known that the probable QGP phase is not strictly treated in the present version of UrQMD model for the early-stage HICs. However, the failure of fluid dynamical models to get the k_T -dependence of the HBT radii [1] suggests that flow is not the only aspect that influences the observed k_T -dependence of HBT radii. A realistic hadronic cascade model such as UrQMD can thus throw light on what other mechanisms during the

late freeze-out stage induce strong coordinate-momentum correlations and thereby generate the observed strong k_T -dependence of the HBT radii. With this equipment, the excitation functions of the HBT radii of negatively charged pions are calculated systematically. In this paper, we focus on RHIC energies, where the biggest challenge is faced by the current theoretical models. The femtoscopy results at lower energies will be presented in a further study [41].

The correlation function of two particles is decomposed in Pratt's (so-called longitudinal co-moving system "Out-Side-Long") three-dimensional convention (Pratt-radii). The three-dimensional correlation function is fit with the standard Gaussian form:

$$C(q_O, q_S, q_L) = 1 + \lambda \exp(-R_L^2 q_L^2 - R_O^2 q_O^2 - R_S^2 q_S^2 - 2R_{OL}^2 q_O q_L), \quad (1)$$

in which q_i and R_i are the components of the pair momentum difference $\mathbf{q} = \mathbf{p}_2 - \mathbf{p}_1$ and the homogeneity length (Pratt-radii) in the i direction, respectively. The λ is the incoherence factor, which lies between 0 (complete coherence) and 1 (complete incoherence) in realistic HICs. R_{OL} represents the cross-term. For mass-symmetric colliding system, the R_{OL} vanishes automatically at mid-rapidity due to the longitudinal reflection symmetry and is also found to be negligible in our present calculations. Furthermore, in the present UrQMD calculations at RHIC energies, the Coulomb and other potential interactions are not considered (the "cascade mode" is used) due to the excessive computing times which would have been used otherwise. The Coulomb final state interactions are not taken into account in the analyzing program CRAB.

Fig. 1 gives the transverse momentum k_T dependence ($\mathbf{k}_T = (\mathbf{p}_{1T} + \mathbf{p}_{2T})/2$) of the Pratt-radii R_L (left plots), R_O (middle plots), and R_S (right plots) at nucleon-nucleon center-of-mass energies $\sqrt{s_{NN}} = 30, 62.4, 130$, and 200 GeV (plots from top to bottom) in Au+Au reactions. The experimental results at energies $\sqrt{s_{NN}} = 62.4, 130$, and 200 GeV for central collisions ($< 15\%$, $< 10\%$, and $< 5\%$ of the total cross section σ_T , respectively) and at mid-rapidities ($|\eta_{cm}| < 0.5$) are taken from Refs. [22, 23, 24, 25, 26]. The experimental error bars are shown as the sum of both statistical and systematic errors. The corresponding calculations with the same trigger- and acceptance- conditions as in the experiments are shown, as well as the lower energy case $\sqrt{s_{NN}} = 30$ GeV for central collisions ($< 15\%$ of σ_T).

Both the absolute values and the decrease of the Pratt-radii R_L and R_S with transverse

momentum is reproduced by the present model calculations very well. The origin of the decrease of the Pratt-radii with the increase of transverse momentum is still under discussion: it may be caused by the strong underlying transverse flow [24], or, by the temperature inhomogeneities within the hadron source (point of view of the hydrodynamics model) [31]. Here, it is also seen that the calculated k_T -dependence of R_S is somewhat flatter than that of R_L , which implies that flow effects on the k_T -dependence of the Pratt-radii can at least not be excluded. Besides the flow effect, the surface-like emission characteristic of microscopic models should play significantly (or even dominant) role on HBT parameters as well because also other Cascade/Boltzmann calculations (see e.g., the Relativistic Quantum Molecular Dynamics model (RQMD) [1, 29], the Hadronic Rescattering Model (HRM) [3], and A Multi-Phase Transport model (AMPT) [46]) can reproduce the k_T dependence of Pratt radii (almost) equally well. The transport of the hadronic gas, or the final state hadronic 'corona' dynamics, should be further investigated since the QGP image is obscured by the hadronic 'corona' [19, 42, 43, 44]. The UrQMD calculations of R_L and R_S reproduce the experimental data well within the error bars, while the calculated R_O 's are larger than the experimental data — the R_O is about 25% too large. We must conclude that at RHIC, larger ratios of R_O and R_S are seen from hadron transport model than expected. Similar observations have also been reported from most of other model calculations (c.f. [1, 3, 19, 20, 21, 45, 46, 47]). Ref. [28] has argued that the origin of this HBT-puzzle might be multifaceted.

Fig. 2 shows the k_T -dependence of the Pratt-radii in Au+Au reaction at $\sqrt{s_{NN}} = 200$ GeV for four centralities: 0 – 5%, 10 – 20%, 30 – 50%, and 50 – 80% of total cross section. Here, a pseudo-rapidity cut $|\eta_{cm}| < 0.5$ has been chosen. For better visibility, we have shifted in the figure the values of the radii by 0, 5, 10, and 15 fm for the four centralities. It is very interesting to see that our calculations for the centrality dependence of Pratt-radii are in reasonably good agreement with the experimental data. The important observation, however, is that the calculated R_O values tend to deviate from the data for central reactions by $\approx 20\%$, while they agree at midcentral and peripheral collisions.

The centrality dependence of the Pratt-radii can be seen more clearly from Fig. 3, which shows the Pratt-radii at $k_T = 250 \sim 350$ MeV/c as a function of the number of participants N_{part} . The quantity $\sqrt{R_O^2 - R_S^2}$ is also shown for comparison. In spite of the reasonable results on the centrality dependence of the Pratt-radii, the calculated quantity $\sqrt{R_O^2 - R_S^2}$ obviously deviates from that extracted from data for the most central collisions: it is about

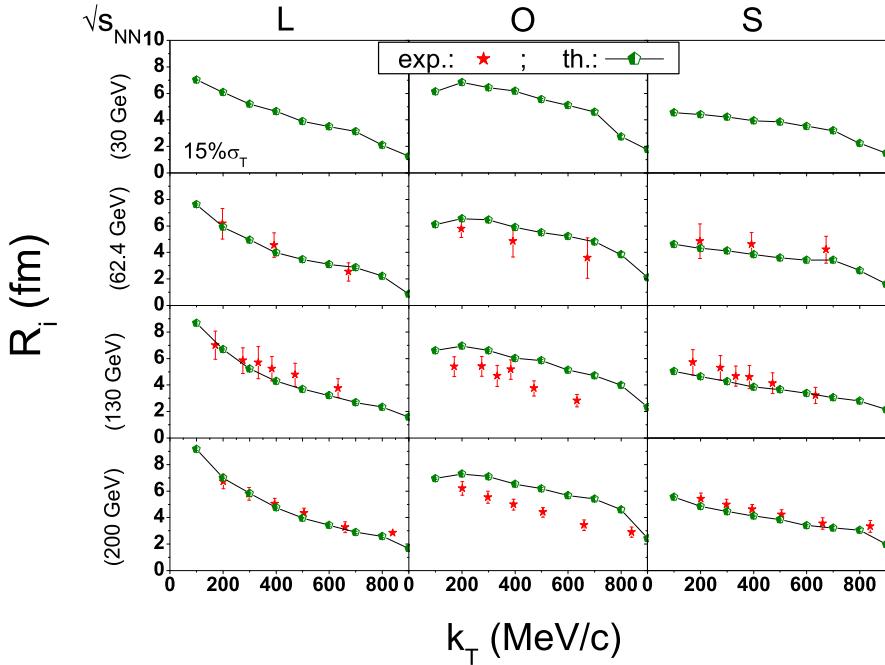


FIG. 1: (Color online) Transverse momentum k_T dependence (at midrapidity) of the Pratt-radii R_L , R_O , and R_S in Au+Au collisions at $\sqrt{s_{NN}} = 30$, 62.4, 130, and 200 GeV. Experimental data for the latter three cases are also shown [22, 23, 24, 25, 26]. The experimental errors are the sums of both statistical and systematic errors.

twice as large as measured by experiments. In previous UrQMD calculations on elliptic flow at RHIC it was found that only $\sim 60\%$ of the observed elliptic flow is produced [37], which is probably due to a smaller anisotropy in the pressure gradients in the early stage of RHIC collisions in the UrQMD simulations compared to hydrodynamics. Based on Ref. [13], the R_O contains the contributions from temporal extent of the source and becomes larger with a smaller transverse freeze-out momentum of particle pairs with a certain duration time. While the expansion has no effect on the R_S . The calculated larger R_O and, correspondingly, the larger calculated quantity $\sqrt{R_O^2 - R_S^2}$ in comparison to the data might therefore be related to the elliptic flow problem in the model. The pion freeze-out volume V_f has been investigated thoroughly experimentally [7]. V_f can be expressed as $V_f = (2\pi)^{3/2} R_L R_S^2$. The linear increase of V_f with N_{part} is expected if the pions freeze out at a constant density ρ_f at a certain beam energy as observed in Ref. [7] and implied in Ref. [1]. It can be explained

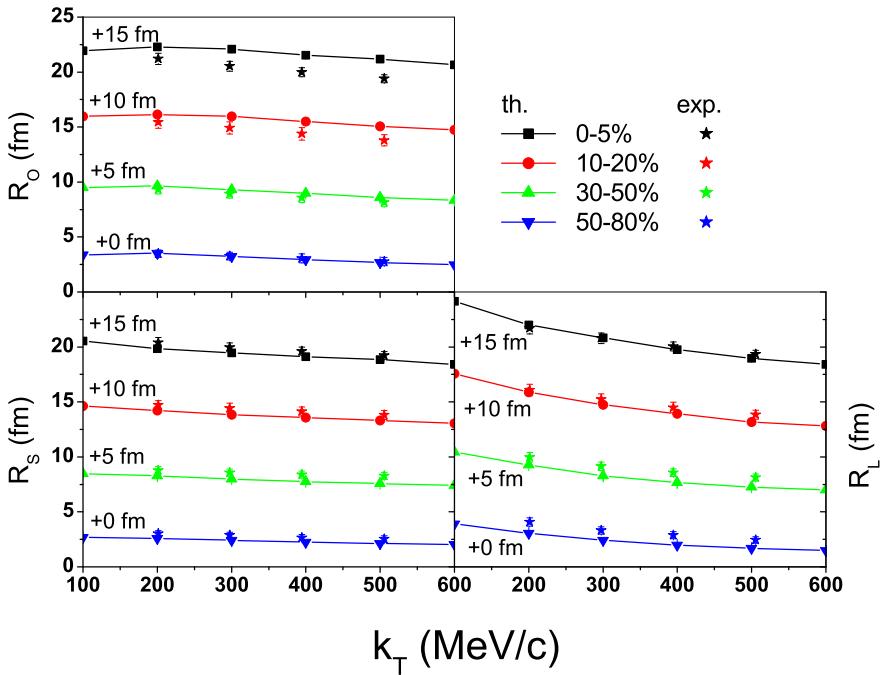


FIG. 2: (Color online) Midrapidity k_t -dependence of Pratt-radii in Au+Au reaction at $\sqrt{s_{NN}} = 200$ GeV for four centralities: 0 – 5%, 10 – 20%, 30 – 50%, and 50 – 80% of the total cross section, which are shifted by 15, 10, 5, and 0 fm, respectively. Experimental data are taken from Ref. [24].

reasonably well by the present model, although a smaller "thermal ellipse" is predicted due to a little shorter R_L and R_S values, as shown.

The calculations for central Cu+Cu collisions are shown in Fig. 3 (solid dots), which are in line with the centrality dependence of the HBT space-time structure calculated for Au+Au collisions. This implies that the participant multiplicity is a very good scaling variable, which drives the geometry (HBT radii) at mid-rapidity, at least for mid-size to heavy systems. In order to check this, the k_T -dependence of the ratios of the Pratt-radii between different systems is shown in Fig. 4. The radius ratios shown are from (a), Cu+Cu vs. p+p, (b), Au+Au vs. p+p, and (c), Au+Au vs. Cu+Cu. In order to read the figure more conveniently, the R_O and R_S ratios are shifted by 5 and 10, respectively. In the p+p calculation, the non-femtoscopic correlations at large relative momenta are also seen, that is, the pion correlations function saturates at large relative momentum, but the value is not equal to 1, which was also implied by the preliminary data reported recently

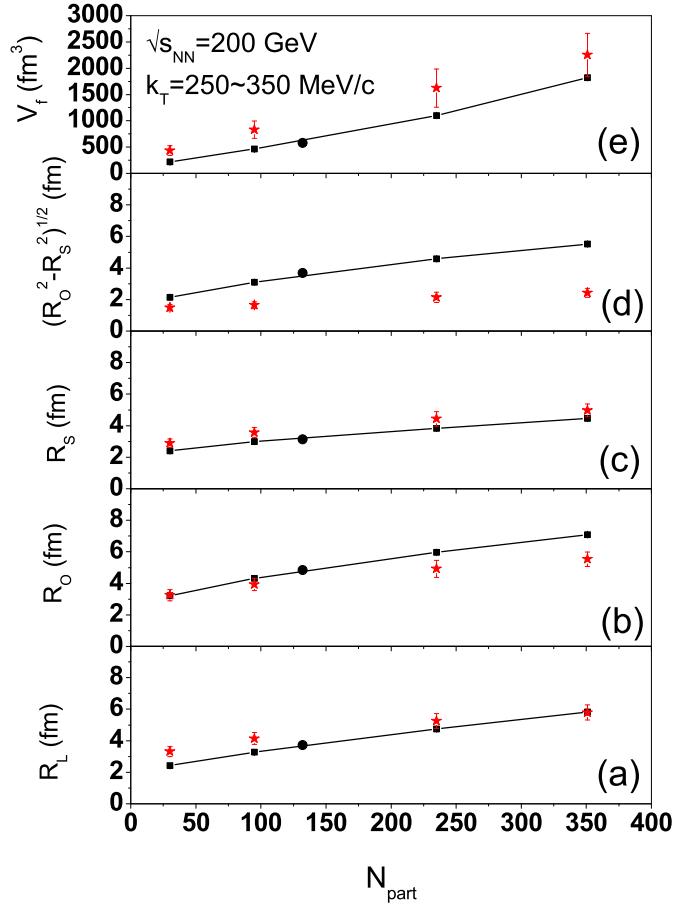


FIG. 3: (Color online) Centrality dependence of the Pratt-radii ((a)-(c)), the quantity $\sqrt{R_O^2 - R_S^2}$ (in (d)), and the freeze-out volume V_f ((e)) at $k_T = 250 \sim 350 \text{ MeV}/c$, in Au+Au collisions at $\sqrt{s_{NN}} = 200 \text{ GeV}$. Experimental data are taken from Ref. [24]. The calculated results for central Cu+Cu collisions shown with solid dots are perfectly located on the Au+Au systematic curves.

by Ref. [14]. We eliminate this effect by multiplying a constant into the parametrization of the correlation function. The R_L and R_S values in p+p collisions can be reproduced well, while the calculated R_O values are again larger than the experimental data, similar to the nucleus-nucleus collisions. This might be the origin of the whole puzzle, namely that the HBT-correlations are somewhat incorrectly put into the model in the elementary p+p dynamics. Figs. 4 (a) and (b) show that the calculated R_L and R_S ratios, reproduce the experimental data reasonably well. They are almost flat as a function of k_T , which means the k_T -dependence of the Pratt-radii still exists in the elementary p+p collisions at RHIC

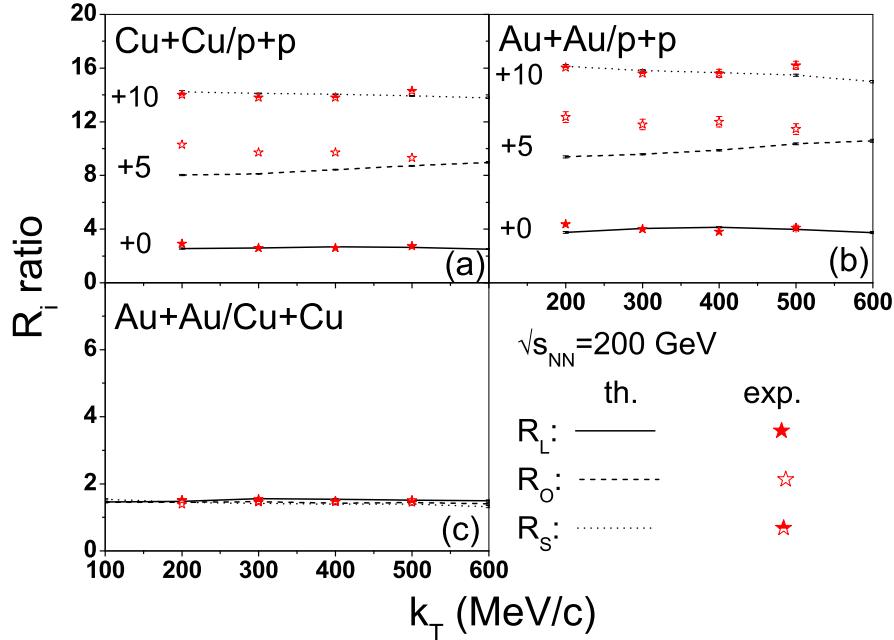


FIG. 4: (Color online) k_T -dependence of the ratios of Pratt-radii between different systems: (a), Cu+Cu vs. p+p, (b), Au+Au vs. p+p, and (c), Au+Au vs. Cu+Cu. Central collisions at $\sqrt{s_{NN}} = 200$ GeV and a mid-rapidity cut are chosen. In (a) and (b), the ratios are shifted by 5 and 10, respectively. The preliminary experimental data are taken from Ref. [14].

energies.

The fact that the k_T dependence of R_L and R_S radii in p+p collisions is similar to AA reaction is puzzling at first glance. In order to explore the origin of the k_T dependence in pp and AA, we randomly exchange the momentum vectors of the pions at freeze-out and recalculated the k_T -dependence of Pratt radii in the p+p (solid lines with open square symbols) and the most central Au+Au (dotted lines with open square symbols, rescaled by the Pratt radii at $k_T = 200$ MeV/c in the p+p collisions) collisions at RHIC energy $\sqrt{s_{NN}} = 200$ GeV, as shown in Fig. 5. We also show the standard calculation results (solid squares) and the experimental data (stars) in p+p collisions. After considering the random mixture of the momenta of freeze-out pions, the k_T dependence of Pratt radii essentially vanishes, especially in the transverse direction. This is a clear indication that space-momentum correlations drive the behavior of the Pratt radii with increasing k_T both in AA and pp! However,

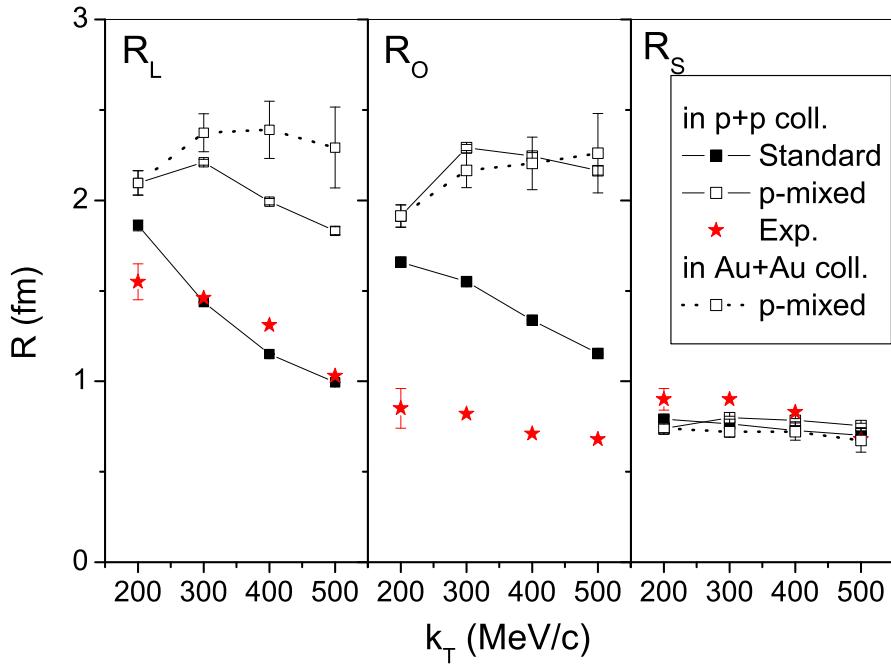


FIG. 5: (Color online) k_T -dependence of the Pratt-radii R_L (left plot), R_O (middle), and R_S (right) in the p+p and the most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The Pratt radii in Au+Au collisions are rescaled by the Pratt radii at $k_T = 200$ MeV/c in the p+p collisions. The standard calculations (titled as "standard") as well as the calculations after considering the random mixture of the momenta of freeze-out pions (titled as "p-mixed") are shown. The preliminary experimental data for p+p collisions are shown with stars.

it is important to stress that the origin of the space-momentum correlation in p+p is most probably due to jet-like structures and not flow.

Since the UrQMD model gives too large a R_O value in p+p collisions, the calculated R_O -ratio between Au+Au (or Cu+Cu) and p+p is smaller than the experimental data, in particular at low transverse momenta. This phenomenon disappears when we consider the Pratt-radii-ratios between two heavy systems, for examples, between Au+Au and Cu+Cu, in Fig. 3 (c). It is interesting to see that for the Pratt-radii-ratios between Au+Au and Cu+Cu collisions, all radii-ratios are flat with k_T and approach ~ 1.4 , which is equal to the ratio between the initial radii of nuclei.

To summarize, by using the CRAB program, we analyzed the evolution of the Pratt-

radii R_L , R_O , and R_S at RHIC energies in collisions simulated by the UrQMD transport model. The calculated transverse momentum-, centrality-, and system dependence of the Pratt-radii are in reasonable agreement with the experimental data. The calculated R_O values for central collisions are $\sim 25\%$ larger as compared to experimental data. As a consequence, the extracted quantity $\sqrt{R_O^2 - R_S^2}$ of the pion emission source is somewhat larger than experimental estimates.

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[1] M. A. Lisa, S. Pratt, R. Soltz and U. Wiedemann, Ann. Rev. Nucl. Part. Sci. **55**, 357 (2005)

[2] M. A. Lisa [the STAR Collaboration], Acta Phys. Polon. B **35**, 37 (2004)

[3] T. J. Humanic, Int. J. Mod. Phys. E **15**, 197 (2006)

[4] E. Frodermann, U. Heinz and M. A. Lisa, arXiv:nucl-th/0602023.

[5] M. A. Lisa, U. W. Heinz and U. A. Wiedemann, Phys. Lett. B **489**, 287 (2000)

[6] J. Adams *et al.* [STAR Collaboration], Phys. Rev. Lett. **93**, 012301 (2004)

[7] D. Adamova *et al.* [CERES Collaboration], Phys. Rev. Lett. **90**, 022301 (2003)

[8] I. G. Bearden *et al.*, Phys. Rev. C **58**, 1656 (1998).

[9] D. Adamova *et al.* [CERES collaboration], Nucl. Phys. A **714**, 124 (2003)

[10] P. Chung *et al.*, Phys. Rev. Lett. **91**, 162301 (2003)

[11] L. Ahle *et al.* [E802 Collaboration], Phys. Rev. C **66**, 054906 (2002)

[12] P. F. Kolb and U. W. Heinz, Invited review for 'Quark Gluon Plasma 3'. Editors: R.C. Hwa and X.N. Wang, World Scientific, Singapore. arXiv:nucl-th/0305084.

[13] B. Tomasik and U. A. Wiedemann, Invited review for Quark Gluon Plasma 3, eds. R.C. Hwa and X.-N. Wang, World Scientific. In *Hwa, R.C. (ed.) et al.: Quark gluon plasma* 715-777.

arXiv:hep-ph/0210250.

- [14] Z. Chajecki, arXiv:nucl-ex/0511035.
- [15] R. Nouicer, arXiv:nucl-ex/0512044.
- [16] M. Lisa, arXiv:nucl-ex/0512008.
- [17] D. Adamova *et al.* [CERES Collaboration], Nucl. Phys. A **698** (2002) 253.
- [18] H. Appelshauser, J. Phys. G **30**, S935 (2004)
- [19] S. Soff, S. A. Bass and A. Dumitru, Phys. Rev. Lett. **86**, 3981 (2001)
- [20] S. Soff, S. A. Bass, D. H. Hardtke and S. Y. Panitkin, Phys. Rev. Lett. **88**, 072301 (2002)
- [21] D. Zschiesche, H. Stöcker, W. Greiner, and S. Schramm, Phys. Rev. C **65**, 064902 (2002)
- [22] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **93**, 152302 (2004)
- [23] B. B. Back *et al.* [PHOBOS Collaboration], arXiv:nucl-ex/0409001.
- [24] J. Adams *et al.* [STAR Collaboration], Phys. Rev. C **71**, 044906 (2005)
- [25] C. Adler *et al.* [STAR Collaboration], Phys. Rev. Lett. **87**, 082301 (2001)
- [26] K. Adcox *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **88**, 192302 (2002)
- [27] U. W. Heinz and P. F. Kolb, arXiv:hep-ph/0204061.
- [28] S. Pratt and D. Schindel, arXiv:nucl-th/0511010.
- [29] M. A. Lisa *et al.* [E895 Collaboration], Phys. Rev. Lett. **84**, 2798 (2000).
- [30] S. Kniege *et al.* [NA49 Collaboration], J. Phys. G **30**, S1073 (2004)
- [31] T. Csorgo, M. Csanad, B. Lorstad and A. Ster, Acta Phys. Hung. A **24**, 139 (2005)
- [32] D. H. Rischke and M. Gyulassy, Nucl. Phys. A **597**, 701 (1996)
- [33] D. H. Rischke and M. Gyulassy, Nucl. Phys. A **608**, 479 (1996)
- [34] S. A. Bass *et al.*, [UrQMD-Collaboration], Prog. Part. Nucl. Phys. **41**, 255 (1998).
- [35] M. Bleicher *et al.*, [UrQMD-Collaboration], J. Phys. G: Nucl. Part. Phys. **25**, 1859 (1999).
- [36] E. L. Bratkovskaya, M. Bleicher, M. Reiter, S. Soff, H. Stöcker, M. van Leeuwen, S. A. Bass, W. Cassing, Phys. Rev. C **69**, 054907 (2004).
- [37] X. Zhu, M. Bleicher and H. Stöcker, Phys. Rev. C **72**, 064911 (2005)
- [38] S. E. Koonin, Phys. Lett. B **70** (1977) 43.
- [39] S. Pratt *et al.*, Nucl. Phys. A **566** (1994) 103C.
- [40] S. Pratt, CRAB version 3, <http://www.nscl.msu.edu/~pratt/freecodes/crab/home.html>
- [41] Q. Li, M. Bleicher, and H. Stöcker, in preparation, 2006.
- [42] T. Hirano and M. Gyulassy, arXiv:nucl-th/0506049.

- [43] K. Werner, arXiv:hep-ph/0603064.
- [44] K. Werner, arXiv:hep-ph/0603195.
- [45] D. Molnar and M. Gyulassy, Phys. Rev. Lett. **92**, 052301 (2004)
- [46] Z. Lin, C. M. Ko and S. Pal, Phys. Rev. Lett. **89**, 152301 (2002)
- [47] T. Hirano and K. Tsuda, Phys. Rev. C **66**, 054905 (2002)